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# AMENDMENT TRANSMITTAL LETTER

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INVENTION:
PRILLING METHOD

INVENTOR(s): JAMES A. KWEEDER ET AL.

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# PERRY'S CHEMICAL ENGINEERS' HANDBOOK

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# PHASE CONTACTING AND LIQUID-SOLID PROCESSING

...ical engineering literature, it is customary to treat agitation, ...ixing, two-phase flow (including slurry transportation), and ...g as discrete, multipurpose operations for which the princi... ...equipment design and operation can be stated generally and ...apted to different specific process ends. They are so presented ... this section, two-... *Handbook:* agitation and paste mixing in this section, two-... ...ow in Sec. 5, and spraying in Sec. 18. It is also customary to ...th some process goals dependent on solid-liquid contactors in ... single-purpose operations that may employ a variety of ...ent options. Such operations include adsorption, colloiding, ...ization, flocculation, ion exchange, and leaching. Again, the ...is followed in the *Handbook*, the equipment for each of these ...ing treated in an individual subsection of Sec. 19, except for ...are omitted. Colloiding has been left out because its special ...haracter makes it of less wide interest to chemical engineers than the others and because in the equipment sense it concerns liquid-liquid emulsions more often than it does liquid-solid suspensions. The interested reader is referred to the many reference texts and monographs on colloid chemistry and colloiding. Flocculation has not been included because the emphasis is generally less on equipment than on implementation of principles by selection of flocculating agents and by procedure. Gravity settlers, described later in this section, are in fact often simultaneous flocculators and separators. In this connection flocculation is discussed briefly later in the subsection "Flocculation"; it is also considered by Gale (in Purchas, *Solid/Liquid Separation Equipment Scale-Up*, Uplands Press, Croydon, England, 1977, pp. 46 ff.) and by Stevenson (ibid., pp. 127 ff.). Some of the chemical engineering implications of flocculation are summarized by Porter, Flood, and Rennier, *Chem. Eng.*, 73(13), 141 (1966).

# AGITATION OF LOW-VISCOSITY PARTICLE SUSPENSIONS

REFERENCES: Holland and Chapman, *Liquid Mixing and Processing in Stirred Tanks*, Reinhold, New York, 1966. Jordon, *Chemical Process ...ment*, part 1, Interscience, New York, 1968, p. 111. Nagata, *Mixing ... and Applications*, Wiley, New York, 1975. Oldshue and Todd, in ...er *Encyclopedia of Chemical Technology*, 3d ed., vol. 15, Wiley, ..., 1981, p. 604. Parker, *Chem. Eng.*, 71(12), 165 (1964). Quillen, ...g., 61(12), 179 (1954). Uhl and Gray (eds.), *Mixing: Theory and ...*, vol. 1, Academic, New York, 1966; vol. 2, 1967. Sterbacek and Tausk, ... *the Chemical Industry*, trans. by Mayer and ed. by Bourne, Per...don, 1965. Zlokarnik, in *Ullmann's Encyklopädie der technischen ...*, ...ili ed., vol. 2, Verlag Chemie, Weinheim, Germany, 1972, p. 258.

...of process functions are carried out in vessels stirred by ...impellers. Some examples are (1) blending miscible liquids; ...ing or dispersing immiscible liquids; (3) dispersing a gas ...; (4) promoting heat transfer between the agitated liquid ...-exchange surface; (5) suspending or dispersing particulate ... liquid to produce uniformity, to promote mass transfer ...dissolution), or to initiate and assist chemical reaction; and ...ing particle agglomerate size. Only the latter two of these ... in this section, but material on some of the others will be ...ecs. 10, 18, and 21. Stirred vessels are emphasized in this ... but some mixing operations may be carried out continu... ...urbulence or by mechanical devices in pipes with very little ...ulation when the time for mixing can be short.

## EQUIPMENT

...may be roughly divided into two broad classes: axial-flow ...and radial-flow impellers. The classification depends on the ...the blade makes with the plane of impeller rotation.

**...w Impellers** Axial-flow impellers include all impellers ...e blade makes an angle of less than 90° with the plane of ...opellers and pitched-blade turbines or paddles, as illus... ... 19-1 and 19-2, are representative axial-flow impellers. ...are often used for agitation in tanks smaller than 3.8 $m^3$ ...less than 1.8 m (6 ft) in diameter when less than 2.2 kW ...factory for obtaining the desired process results.

...mixers may be clamped on the side of an open vessel in ...off-center position shown in Fig. 19-10 or bolted to a ...op the top of a closed vessel with the shaft in the same angular, off-center position. This mounting results in a strong top-to-bottom circulation.

Two basic speed ranges are available: 1150 or 1750 r/min with direct drive and 350 or 420 r/min with a gear drive. The high-speed units produce higher velocities and shear rates in the propeller discharge stream and a lower circulation rate throughout the vessel than the low-speed units. For suspension of solids, it is common to use the gear-driven units, while for rapid dispersion or fast reactions the high-speed units are more appropriate.

Propellers may also be mounted near the bottom of the cylindrical wall of a vessel as shown in Fig. 19-3. Such side-entering agitators are used to blend low-viscosity fluids [<0.1 Pa·s (100 cP)] or to keep slowly settling sediment suspended in tanks as large as some 4000 $m^3$ ($10^6$ gal). Mixing of paper pulp is often carried out by side-entering propellers.

Pitched-blade turbines (Fig. 19-2) are used on top-entering agitator shafts instead of propellers when a high axial circulation rate is desired and the power consumption is more than 2.2 kW (3 hp). A pitched-blade turbine near the upper surface of liquid in a vessel is effective for rapid submergence of floating particulate solids.

**Radial-Flow Impellers** Radial-flow impellers have blades which are parallel to the axis of the drive shaft. The smaller multiblade ones are known as "turbines"; larger, slower-speed impellers, with two or four blades, are often called "paddles." The diameter of a turbine is normally between 0.3 and 0.6 of the tank diameter. Turbine impel-

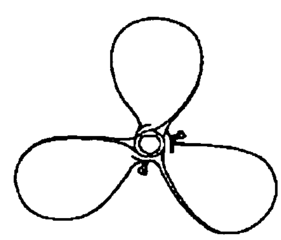

FIG. 19-1 Marine-type mixing propeller.



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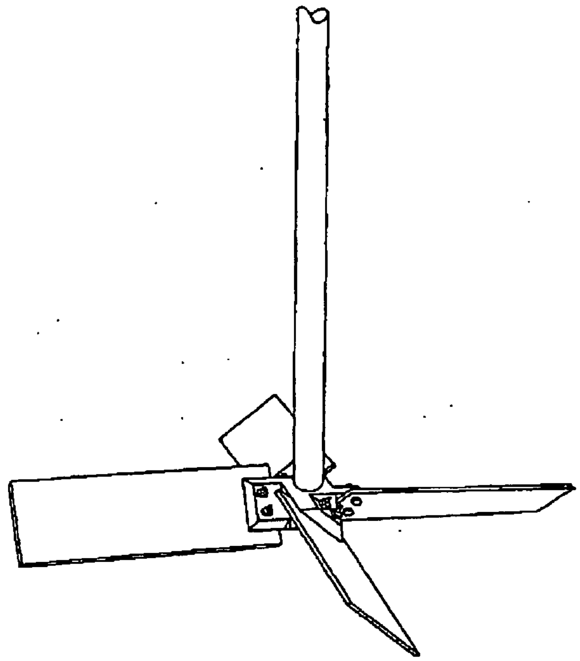

FIG. 19-2 Pitched-blade turbine.

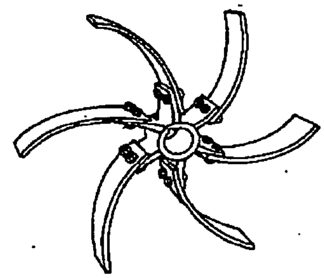

FIG. 19-4 Curved-blade turbine.

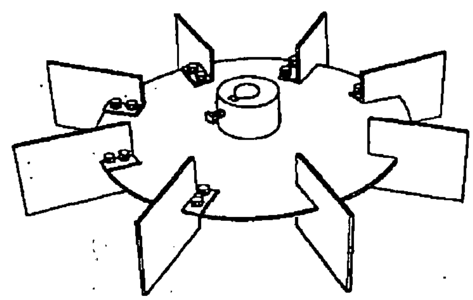

FIG. 19-5 Flat-blade turbine.

lers come in a variety of types, such as curved-blade and flat-blade, as illustrated in Figs. 19-4 and 19-5. Curved blades aid in starting an impeller in settled solids. A paddle agitator has a diameter usually greater than 0.6 of the tank diameter and turns at a slow speed. Construction is often similar to that shown in Fig. 19-4, but with two or four straight blades and with a relatively smaller hub.

Most large-scale agitation of solid-liquid suspensions is done with top-entering turbines or paddles. Power may range from 750 W (1 hp) to as high as 750 kW (1000 hp). The impeller speed is typically between 50 and 150 r/min; but, depending on process conditions, it may go as high as 400 or as low as 15 r/min.

For processes in which corrosion of commonly used metals is a

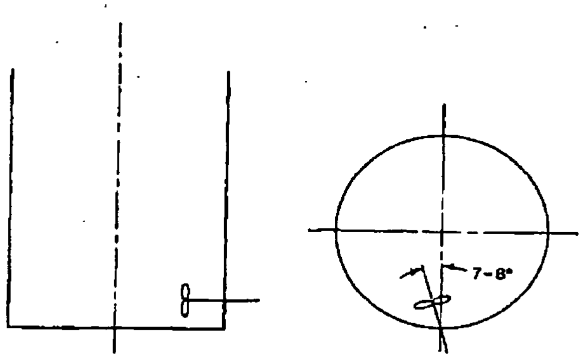


FIG. 19-3 Side-entering propeller mixer.

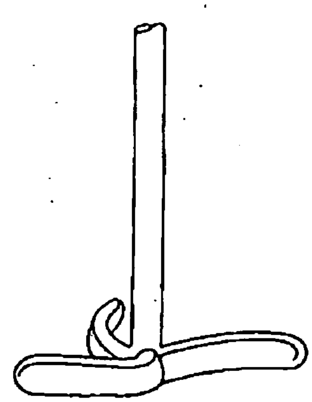

FIG. 19-6 Glassed-steel impeller. (*The Pfaudler Company.*)

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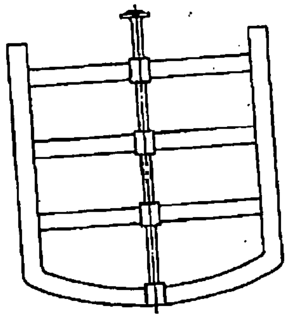

FIG. 19-7 Anchor impeller.

...problem, glass-coated impellers may be economical. A typical mod...ified curved-blade turbine of this type is shown in Fig. 19-6.

**Close-Clearance Stirrers** For some pseudoplastic fluid systems stagnant fluid may be found next to the vessel walls in parts remote from propeller or turbine impellers. In such cases, an "anchor" impeller may be used (Fig. 19-7). The fluid flow is principally circular in the direction of rotation of the anchor. Whether substantial axial or radial fluid motion also occurs depends on the fluid viscosity and the design of the upper blade-supporting spokes. Anchor agitators are used particularly to obtain improved heat transfer in high-consistency fluids.

**Unbaffled Tanks** If a low-viscosity liquid is stirred in an unbaffled tank by an axially mounted agitator, there is a tendency for a swirling flow pattern to develop regardless of the type of impeller. Figure 19-8 shows a typical flow pattern. A vortex is produced owing to centrifugal force acting on the rotating liquid. In spite of the presence of a vortex, satisfactory process results often can be obtained in an unbaffled vessel. However, there is a limit to the rotational speed that may be used, since once the vortex reaches the impeller, severe air entrainment may occur. In addition, the swirling mass of liquid often generates an oscillating surge in the tank, which coupled with the deep vortex may create a large fluctuating force acting on the mixer shaft.

Vertical velocities in a vortexing low-viscosity liquid are low relative to circumferential velocities in the vessel. Increased vertical circulation rates may be obtained by mounting the impeller off center, as illustrated in Fig. 19-9. This position may be used with either turbines or propellers. The position is critical, since too far or too little off center in one direction or the other will cause greater swirling, erratic vortexing, and dangerously high shaft stresses. Changes in viscosity and tank size also affect the flow pattern in such vessels. Off-center mountings have been particularly effective in the suspension of paper pulp.

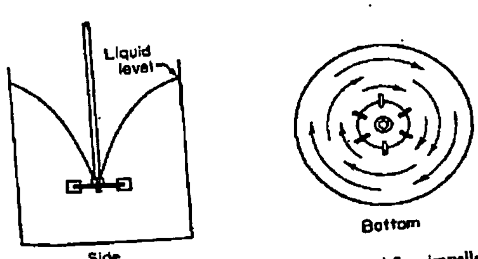


FIG. 19-8 Typical flow pattern for either axial- or radial-flow impellers in an unbaffled tank.

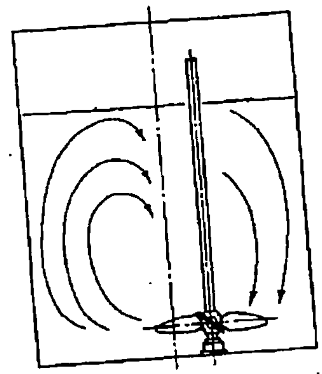

FIG. 19-9 Flow pattern with a paper-stock propeller, unbaffled; vertical off-center position.

With axial-flow impellers, an angular off-center position may be used. The impeller is mounted approximately 15° from the vertical, as shown in Fig. 19-10.

The angular off-center position used with propeller units is usually limited to propellers delivering 2.2 kW (3 hp) or less. The unbalanced fluid forces generated by this mounting can become severe with higher power.

Paddles and anchors normally operate coaxially within unbaffled tanks, since they may have a close clearance with the tank wall.

**Baffled Tanks** For vigorous agitation of thin suspensions, the tank is provided with baffles which are flat vertical strips set radially along the tank wall, as illustrated in Figs. 19-11 and 19-12. Four baffles are almost always adequate. A common baffle width is one-tenth to one-twelfth of the tank diameter (radial dimension). For agitating slurries, the baffles often are located one-half of their width from the vessel wall to minimize accumulation of solids on or behind them.

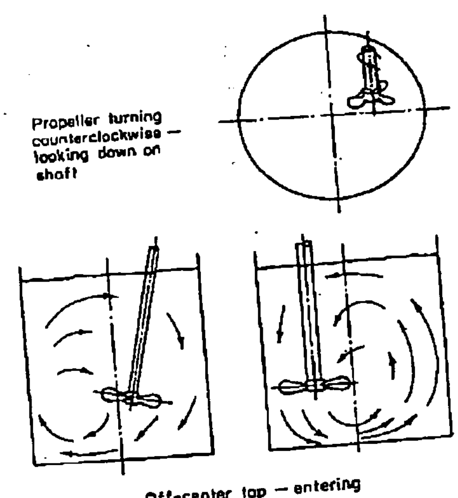


FIG. 19-10 Flow pattern for a propeller in angular off-center position without baffles.

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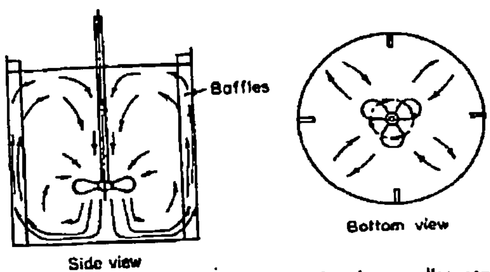


FIG. 19-11 Typical flow pattern in a baffled tank with a propeller or an axial-flow turbine positioned on center.

For Reynolds numbers greater than 10,000, baffles are commonly used with turbine impellers and with on-centerline axial-flow impellers. The flow patterns illustrated in Figs. 19-11 and 19-12 are quite different, but in both cases the use of baffles results in a large top-to-bottom circulation without vortexing or severely unbalanced fluid forces on the impeller shaft.

In the transition region [Reynolds numbers, Eq. (19-1), from 10 to 10,000], the width of the baffle may be reduced, often to one-half of standard width. If the circulation pattern is satisfactory when the tank is unbaffled but a vortex creates a problem, partial-length baffles may be used. These are standard-width and extend downward from the surface into about one-third of the liquid volume.

In the region of laminar flow ($N_{Re} < 10$), the same power is consumed by the impeller whether baffles are present or not, and they are seldom required. The flow pattern may be affected by the baffles, but not always advantageously. When they are needed, the baffles are usually placed one or two widths radially off the tank wall, to allow fluid to circulate behind them and at the same time produce some axial deflection of flow.

## FLUID BEHAVIOR IN MIXING VESSELS

**Impeller Reynolds Number** The presence or absence of turbulence in an impeller-stirred vessel can be correlated with an impeller Reynolds number defined

$$N_{Re} = D_a^2 N \rho / \mu \qquad (19\text{-}1)$$

where $N$ = rotational speed, r/s; $D_a$ = impeller diameter, m (ft); $\rho$ = fluid density, kg/m$^3$ (lb/ft$^3$); and $\mu$ = viscosity, Pa·s [lb/(ft·s)]. Flow in the tank is turbulent when $N_{Re} > 10{,}000$. Thus viscosity alone is not a valid indication of the type of flow to be expected. Between Reynolds numbers of 10,000 and approximately 10 is a transition range in which flow is turbulent at the impeller and laminar in remote parts of the vessel; when $N_{Re} < 10$, flow is laminar only.

Not only is the type of flow related to the impeller Reynolds number, but also such process performance characteristics as mixing time, impeller pumping rate, impeller power consumption, and heat- and

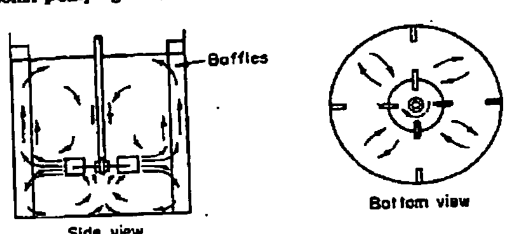


FIG. 19-12 Typical flow pattern in a baffled tank with a turbine positioned on center.

mass-transfer coefficients can be correlated with this dimension[al] group.

**Relationship between Fluid Motion and Process Perfor[-]mance** Several phenomena which can be used to promote vari[ous] processing objectives occur during fluid motion in a vessel.

1. Shear stresses are developed in a fluid when a layer of flu[id] moves faster or slower than a nearby layer of fluid or a solid surface. In laminar flow, the shear stress is equal to the product of fluid vis[-]cosity and velocity gradient or rate of shear. Under laminar-flow con[-]ditions, shear forces are larger than inertial forces in the fluid.

With turbulent flow, shear stress also results from the behavior of transient random eddies, including large-scale eddies which decay in[to] small eddies or fluctuations. The scale of the large eddies depends on equipment size. On the other hand, the scale of small eddies, which dissipate energy primarily through viscous shear, is almost indepen[-]dent of agitator and tank size.

The shear stress in the fluid is much higher near the impeller than it is near the tank wall. The difference is greater in large tanks than in small ones.

2. Inertial forces are developed when the velocity of a fluid changes direction or magnitude. In turbulent flow, inertia forces are larger than viscous forces. Fluid in motion tends to continue in motion until it meets a solid surface or other fluid moving in a dif[-]ferent direction. Forces are developed during the momentum trans[-]fer that takes place. The forces acting on the impeller blades fluc[-]tuate in a random manner related to the scale and intensity of turbulence at the impeller.

3. The interfacial area between gases and liquids, immiscible liq[-]uids, and solids and liquids may be enlarged or reduced by these viscous and inertia forces when interacting with interfacial forces such as surface tension.

4. Concentration and temperature differences are reduced by bulk flow or circulation in a vessel. Fluid regions of different com[-]position or temperature are reduced in thickness by bulk motion in which velocity gradients exist. This process is called bulk diffusion or Taylor diffusion (Brodkey, in Uhl and Gray, op. cit., vol. 1, p. 48). The turbulent and molecular diffusion reduces the difference between these regions. In laminar flow, Taylor diffusion and molec[-]ular diffusion are the mechanisms of concentration- and tempera[-]ture-difference reduction.

5. Equilibrium concentrations which tend to develop at solid-liq[-]uid, gas-liquid, or liquid-liquid interfaces are displaced or changed by molecular and turbulent diffusion between bulk fluid and fluid adjacent to the interface. Bulk motion (Taylor diffusion) aids in this mass-transfer mechanism also.

**Turbulent Flow in Stirred Vessels** Turbulence parameters such as intensity and scale of turbulence, correlation coefficients, and energy spectra have been measured in stirred vessels. However, these characteristics are not used directly in the design of stirred vessels. For further details see Cutter, *Am. Inst. Chem. Eng. J.*, 12, 35[-] (1966).

**Fluid Velocities in Mixing Equipment** Fluid velocities have been measured for various turbines in baffled and unbaffled vessels. Typical data are summarized in Uhl and Gray, op. cit., vol. 1, chap. 4. Velocity data have been used for calculating impeller discharge and circulation rates but are not employed directly in the design of mixing equipment.

**Impeller Discharge Rate and Fluid Head for Turbulent Flow** When fluid viscosity is low and flow is turbulent, an impeller moves fluids by an increase in momentum from the blades which exert a force on the fluid. The blades of rotating propellers and tur[-]bines change the direction and increase the velocity of the fluids.

The pumping rate or discharge rate of an impeller is the flow rate perpendicular to the impeller discharge area. The fluid passing through this area has velocities proportional to the impeller periph[-]eral velocity and velocity heads proportional to the square of these velocities at each point in the impeller discharge stream under tur[-]bulent-flow conditions. The following equations relate velocity head, pumping rate, and power for geometrically similar impellers under turbulent-flow conditions:

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